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INVESTIGATION OF EFFECT OF HYDROGEN SNOW ACCUMULATION ON THE CENTAUR RETROMANEUVER AND THE SURVEYOR PAYLOAD

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Prepared by: J. N. Tulino
J. N. Tulino
Assistant Project Engineer

C. F. Staley
C. F. Staley
Assistant Project Engineer

Approved by: J B Roets
J. B. Roets
Sr. Project Engineer

Pratt & Whitney Aircraft DIVISION OF UNITED AIRCRAFT CORPORATION
FLORIDA RESEARCH AND DEVELOPMENT CENTER

FOREWORD

This report is submitted in compliance with Change Order 18 of Contract NAS8-5623.

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ABSTRACT

A test program was conducted to determine if solid hydrogen would form, adhere to the walls, and block the RL10 interstage and discharge valve vent ducts during the Centaur Retromaneuver. The results of this program have shown that solid hydrogen does form in the ducts and adheres to the interior surface of the vent tube, intermittently building up and breaking off into the stream. At fuel pump inlet pressures of 15 psia, approximately 80% of the interstage vent tube exit area was choked by solid hydrogen. The formation of the solid hydrogen and partial blockage of the vent tubes will affect both the vector and the retrothrust level. Additional tests should be conducted to evaluate various modifications that can be incorporated into the vehicle or engine to either prevent the formation of solid hydrogen, or make its effect on the retromaneuver negligible. These modifications should include:

1. An orifice at the exit plane of the vent tube to maintain the pressure in the tube above the triple line of hydrogen
2. A helium purge to provide a boundary layer between the hydrogen flow stream and the tube wall
3. Application of heat to raise the tube wall temperature to a degree where solid hydrogen would not adhere
4. Use of a larger diameter vent tube to increase the quantity of the solid hydrogen buildup required for significant blockage, thereby increasing the bending stress and the likelihood of the formations breaking away into the stream.

SECTION I
INTRODUCTION

The Centaur vehicle uses hydrogen fuel tank residuals exhausted through vehicle overboard vent tubes on the interstage and discharge cooldown valves and oxygen tank residuals exhausted through the propellant injector to provide retrothrust to accelerate the booster away from the Surveyor payload after it has been separated from the Centaur vehicle. A test program was implemented to determine the following.

1. Ascertain if solid hydrogen (snow) would form in the interstage and discharge cooldown valve vent tubes.
2. Ascertain that if hydrogen snow did form, would it completely block the tube; or if partially blocked, have an effect on the flow rate and thrust vector.
3. Determine the velocity and estimate the momentum of the hydrogen snow particles.

An experimental RL10A-3CM1 engine was modified for the Centaur Retromaneuver program by adding the vehicle interstage and discharge cooldown valve overboard vent ducts. These ducts were instrumented for pressure and temperature in four planes along the axial length. A Mylar radiation shield was incorporated to prevent radiation to the tube from the altitude capsule and the engine. Four small bleed holes were added at the inlet of each tube to provide a hydrogen boundary layer around the outside of the tube to further reduce the tube wall heat transfer to near predicted space conditions. High-speed motion picture cameras were mounted in the altitude capsule to photograph the exit of each vent tube during the test.

Twelve engine tests were conducted in E-7 vertical test stand, which is equipped with a steam exhaust system capable of maintaining an engine environmental capsule pressure of 0.1 to 0.6 psia at the predicted hydrogen vent flows. Included were six tests using the radiation shielded, instrumented vent tubes; two tests with insulated vehicle tubes; one test with an insulated tube coated on the ID with Teflon-filled Kel-F; and three tests to determine the effective area of the vent tubes.

The results of these tests showed that at fuel pump inlet pressures of 30 psia, hydrogen snow formed in the flow stream, but was not attached to the tube. At inlet pressures of 20 psia, the snow was seen intermittently building up and breaking off at the vent tube exit. At inlet pressures of 10 psia and below, snow was observed to build up inside the vent tubes; at 15 psia, up to 80% of the interstage vent tube area appeared to be momentarily blocked as the solid hydrogen intermittently built up and broke off into the stream. There was a higher percentage buildup in vent tubes with the vehicle insulation than in the vent tubes with the Mylar radiation shield. Teflon-filled Kel-F coating of the interior tube surface showed no significant effect on the rate of snow buildup in the tube. The velocity of medium sized particles breaking away from the tube exit was calculated to be 101 mph, resulting in a momentum of 0.039 lb-ft/sec.

A detailed discussion of the test program and results are given in the following sections.

SECTION II
TECHNICAL DISCUSSION

A. GENERAL

The program to determine the effect of hydrogen snow accumulation on the Centaur Retromaneuver and the Surveyor payload was initiated on 10 July 1965. The acquisition of data was in two categories; (1) high-speed motion pictures focused on the exit of each vent tube, and (2) recording pressures and temperatures on the tube.

Initially, due to the low pressure environment (0.1 to 0.6 psia), it was predicted that the major portion of the heat transferred to the tube would be through radiation from the walls of the altitude capsule and from the engine components. Conduction of heat through the tube connections and convection due to recirculation was considered to be negligible (approximately 0.1 Btu/sec). A radiation shield (figure II-1) was constructed around the vent tube by forming a cage of soft aluminum wire insulated from the tube by foam blocks and wrapping this cage with Mylar tape, leaving a 3/4 inch space between the tube and shields. The shield at the inlet of the tube was closed off so that the space was dead-ended to prevent any recirculation. The tube was divided into four planes axially (figure II-2) and each plane instrumented for pressure and temperature to determine the tube wall heat leak and the plane in which blockage occurred by recording changes in absolute and differential pressures. Data from the first test indicated two problems; (1) tube wall heat leak was 0.8 Btu/sec which was greater than predicted, and (2) motion picture resolution at the standard frame speed was not good enough to delineate the snow particles from the gas stream.

To reduce the heat input, four equally spaced 0.070-inch diameter bleed holes were drilled in the vent tube at the inlet. These holes were later increased to a diameter of 0.140 inch. The purpose of the bleed holes was to provide film cooling on the outside of the tube. The camera speed was increased from 400 to 800 frames per second to improve photographic resolution.

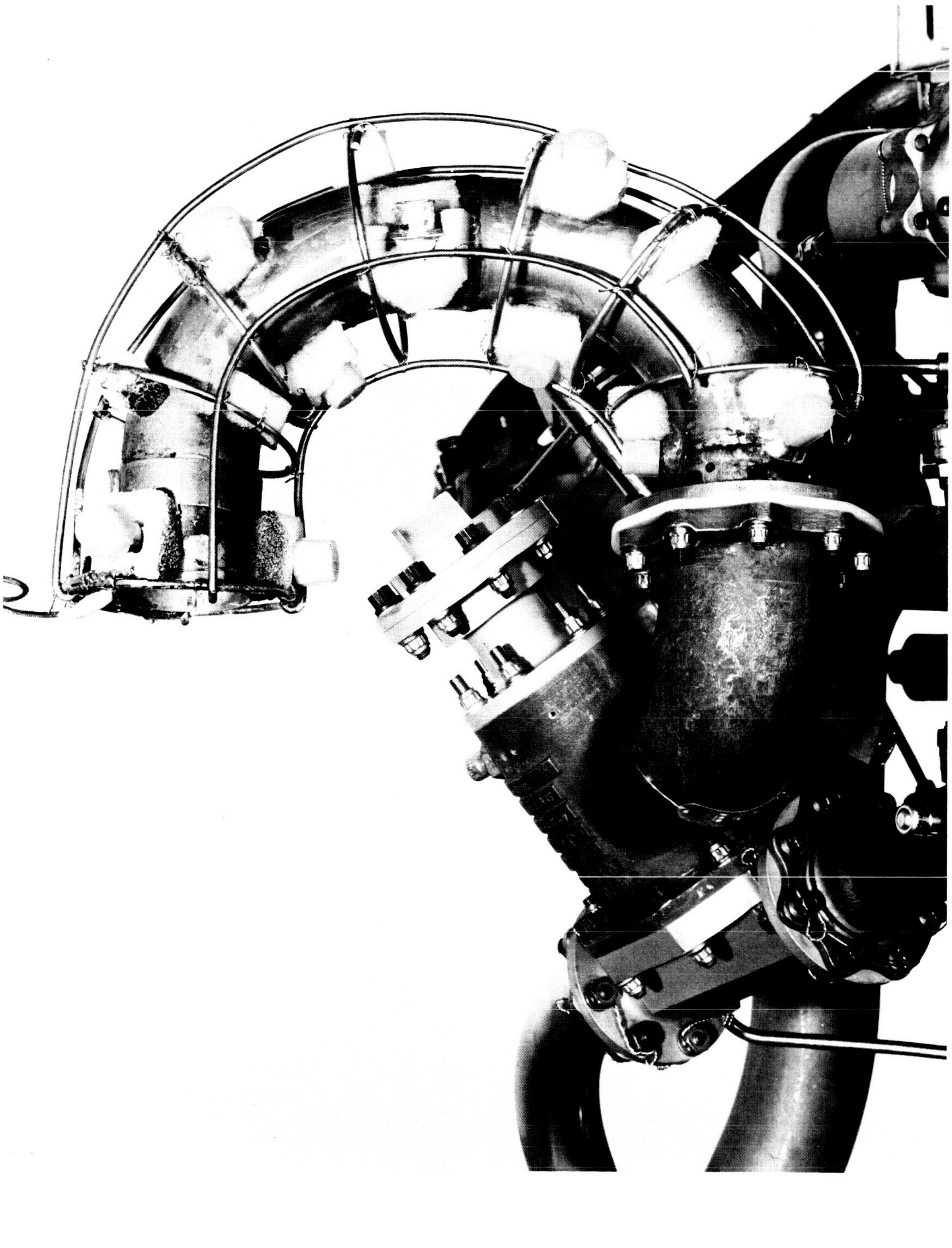

Figure II-1. Discharge Valve Vent Tube Radiation Shield Construction FE 52825

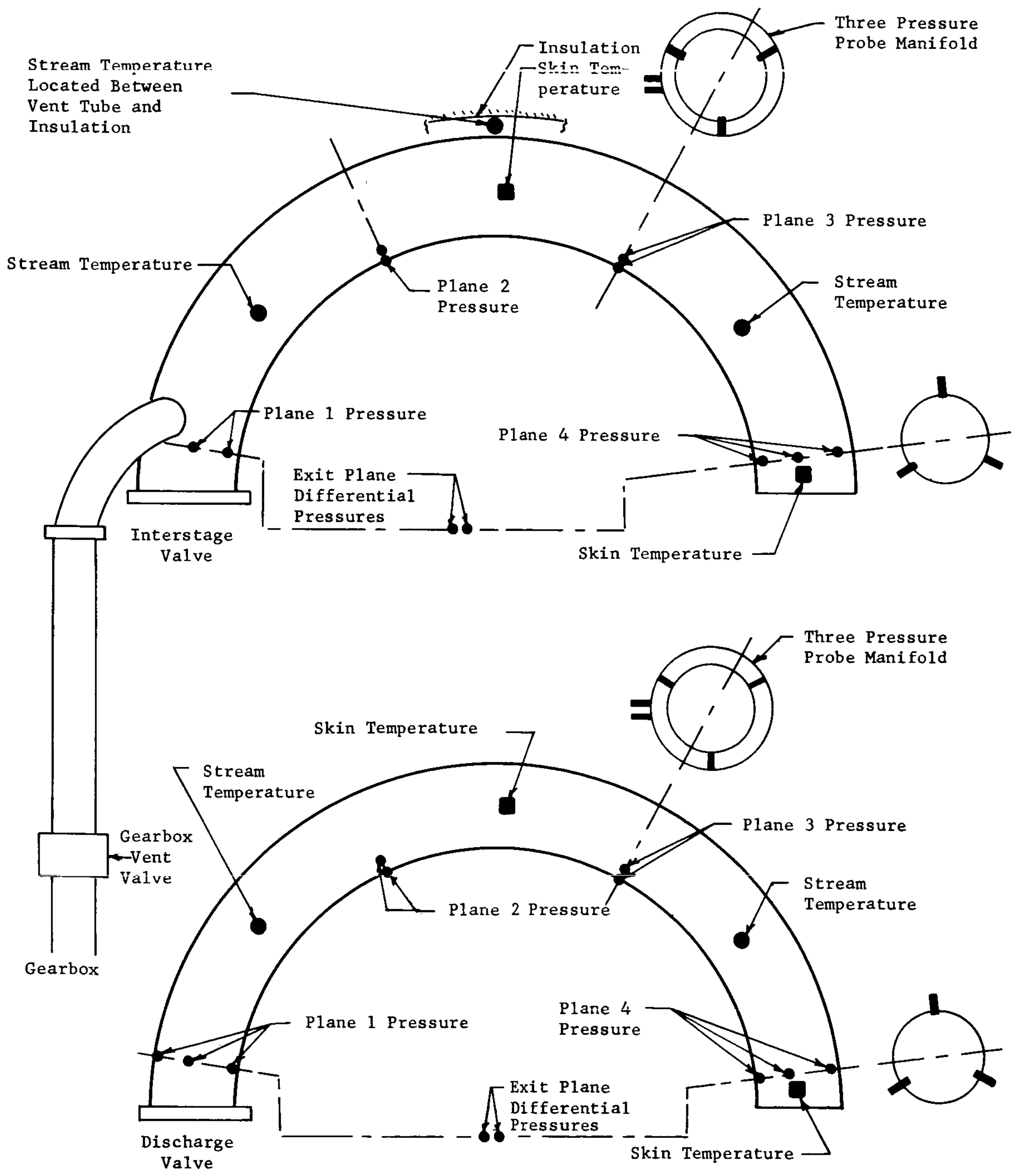

Figure II-2. Instrumentation for Calibration of GD/C Vent Tubes

FD 13360

Tests conducted with fuel pump inlet pressures varied between 30 and 5 psia resulted in inlet conditions varying from liquid to two-phase flow. The interstage and discharge cooldown valve vent tube exit pressures varied from 1.8 to 0.2 psia with varying inlet pressures. With the increased diameter bleed holes (0.140-inch) open, heat leak into the tubes was reduced to an average of 0.03 Btu/sec. There was an intermittent buildup of snow as pump inlet pressure was reduced from 30 to 20 psia, and continued to increase at lower inlet pressures. These tests were repeated using GD/C supplied vehicle vent tubes insulated externally (figure II-3) and an interstage vent tube having the ID coated with an "anti-stick" Teflon-filled Kel-F (figure II-4). These tubes were not instrumented but motion picture analysis showed that the test results were the same as with the instrumented tubes.

Three tests were conducted flowing the vent ducts individually with gaseous, mixed phase, and liquid propellants to determine effective areas to be used for thrust calculations. Table II-1 is a summary of all tests conducted.

B. TEST STAND

Test stand E-7 was used for all tests. This test stand is equipped with a steam driven exhaust system capable of maintaining a 0.1 to 0.6 psia nozzle exit pressure during all phases of engine operation.

C. ENGINE CONFIGURATION

RL10A-3CM1 experimental engine FX-145 was used for these tests. Engine FX-145 was adapted for these tests by adding the interstage and discharge cooldown valve vents shown in figure II-5.

Table II-1. Run Summary of Centaur Retromaneuver Support Testing
Engine FX-145-14 E-7 Stand

Run Number	Configuration	Fuel Pump Inlet Pressure, psia	Inlet Phase	Remarks
143.01	Instrumented ducts. Four 0.070-inch diameter bleed holes at duct inlets.	30-20	Liquid	High intensity camera lights on full run.
143.02	Instrumented duct, bleed holes capped.	20	Liquid	High intensity camera lights on full run.
143.03	Same as 143.02.	30-20	Liquid	High intensity camera lights on full run. Capsule pressure raised to 1.9 psia.
143.04	Same as 143.02.	30-20	Liquid	Low intensity camera lights - after data points only. Capsule pressure raised to 1.0 psia.
143.05	Instrumented ducts. 0.140-in. dia bleed holes.	30-15	Liquid to Two-Phase	Low intensity camera lights. Purpose to acquire data points only.
143.06	Same as above with immersion temperature probes removed.	20-5	Liquid to Two-Phase	Same as 143.05.
143.07	Standard insulated GD/C ducts - exit pressure instrumentation only.	20-5	Liquid to Two-Phase	Same as 143.05.
143.08	Same as 143.07.	30-20	Liquid	Same as 143.05.
143.09	Same as 143.07.	30-6	Gaseous	Individual ducts flowed - no cameras, no duct internal temperatures recorded.
143.10	Teflon-coated interstage discharge duct only.	20-10	Liquid to Two-Phase	Low intensity camera lights. Purpose to acquire data points only.
143.11	Lox side instrumented with special GMRV.	Lox inlet 40-27	Liquid to Two-Phase	Lox side flowed - fuel side prechilled.
143.12	Instrumented ducts.	30-10	Gaseous	Individual ducts flowed - no cameras, internal duct temperatures.

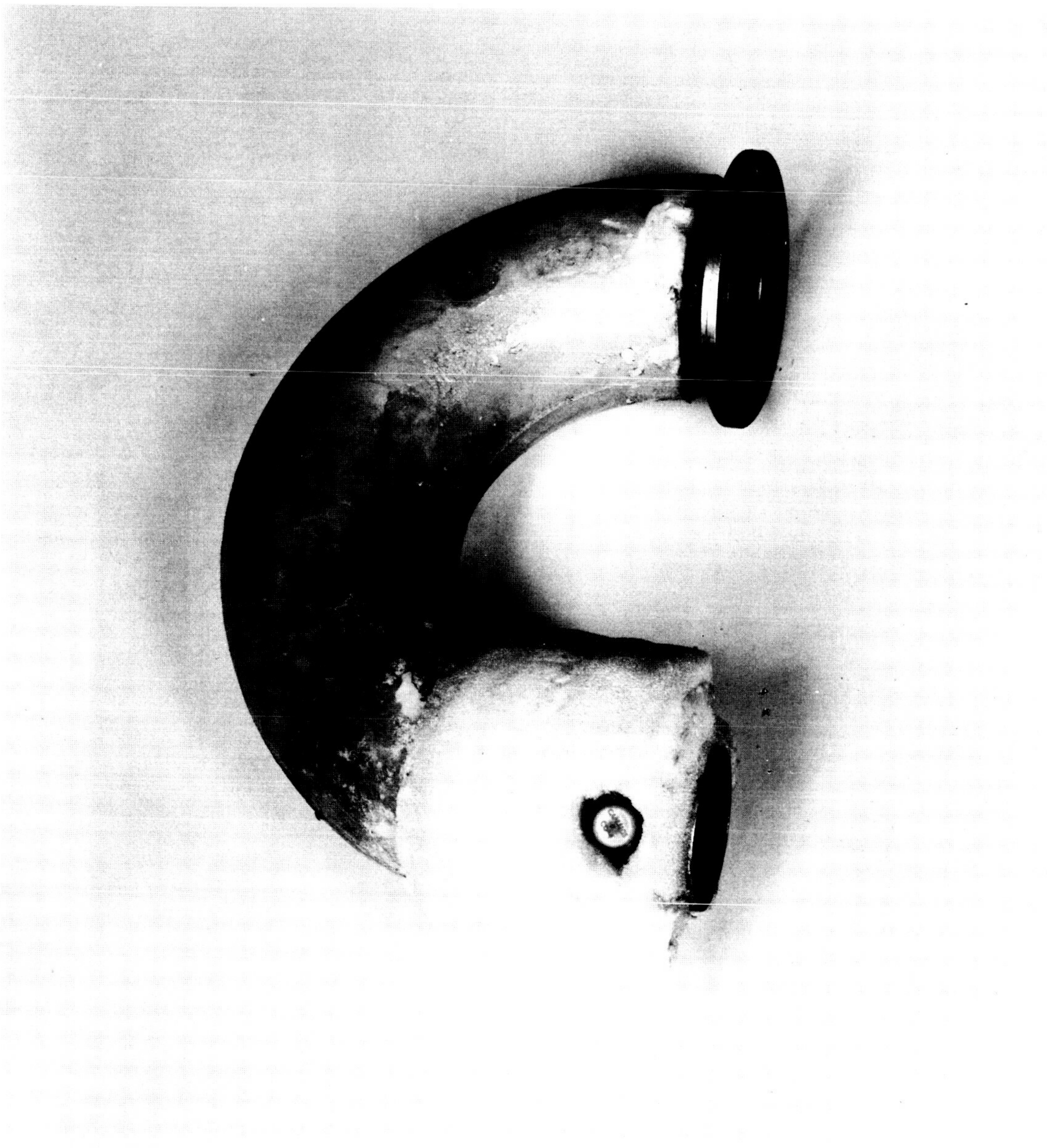

Figure II-3. GD/C Insulated Discharge Vent Tube FE 52826

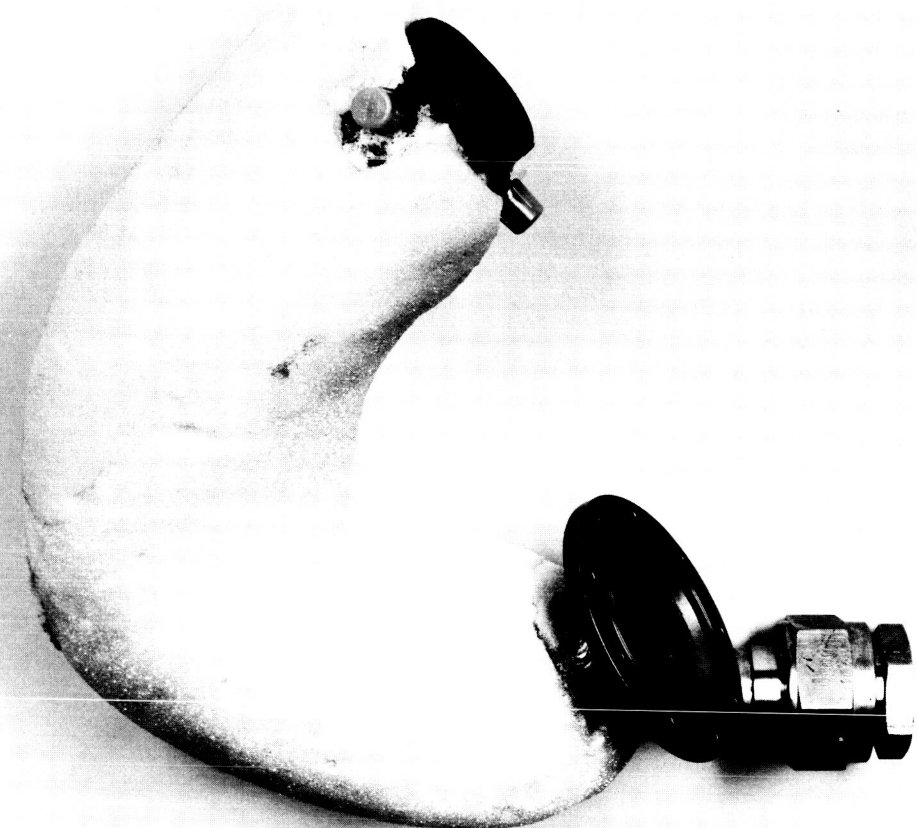

Figure II-4. Interstage Valve Vent Tube with Teflon-Filled Interior Insulation

FE 52827

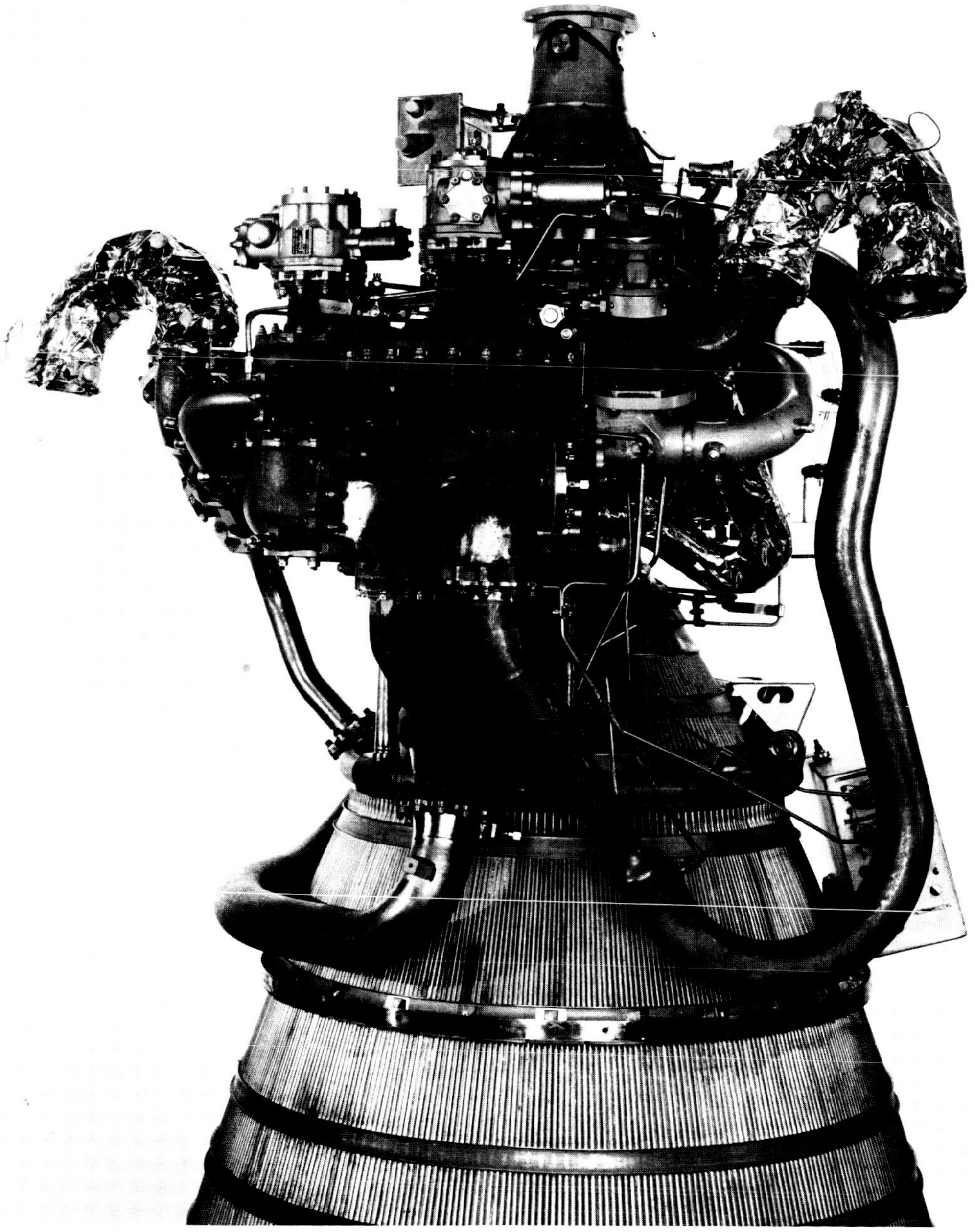

Figure II-5. Engine FX-145 with Radiation Shielded Vent Tubes FE 52824

SECTION III
ANALYSIS OF RESULTS

The photographic test data showed the solid hydrogen forming and adhering to the tube walls to some extent on all runs with liquid or two-phase hydrogen at the pump inlet. The solid hydrogen was continuously forming and breaking away. However, only on the tests with the standard foam insulation was the heat input to the tubes apparently low enough to observe an adverse solid buildup. The most adverse condition photographed showed the tube exit area up to 80% blocked (figure III-1) before breaking away. This occurred with the foam insulated interstage vent tube at a fuel pump inlet pressure of 15 psia.

The major difficulty in attaining space conditions was the indicated high heat input to the vent tubes from external sources associated with the tests. The skin temperature measurements were obtained from Rosemont skin temperature probes and thermocouples located at the tube discharge.

The prerun determination of the heat input from free convection and radiation within the test cell showed it to be small enough (approximately 0.1 Btu/sec) to conduct the test with only nominal radiation shielding and no insulation. However, after the first two runs it was apparent that the heat input to the tubes was much higher than predicted (approximately 0.8 Btu/sec). The actual heat fluxes were calculated using the measured flow rates, the bulk temperatures, and the Rosemont skin temperature probes data shown in figure III-2. The changes in slope of the temperature in figure III-3 reflect the changes in the pump inlet pressure and the back pressure. Even using the actual environmental data obtained, the calculated heat input from the free convection and the radiation was still too low. This fact, and the appreciable turbulence and velocities apparent in the photographs indicate that the assumption of free convection was invalid. Cursory investigations into this area where the forced and free convection modes are both significant did not yield any better results.

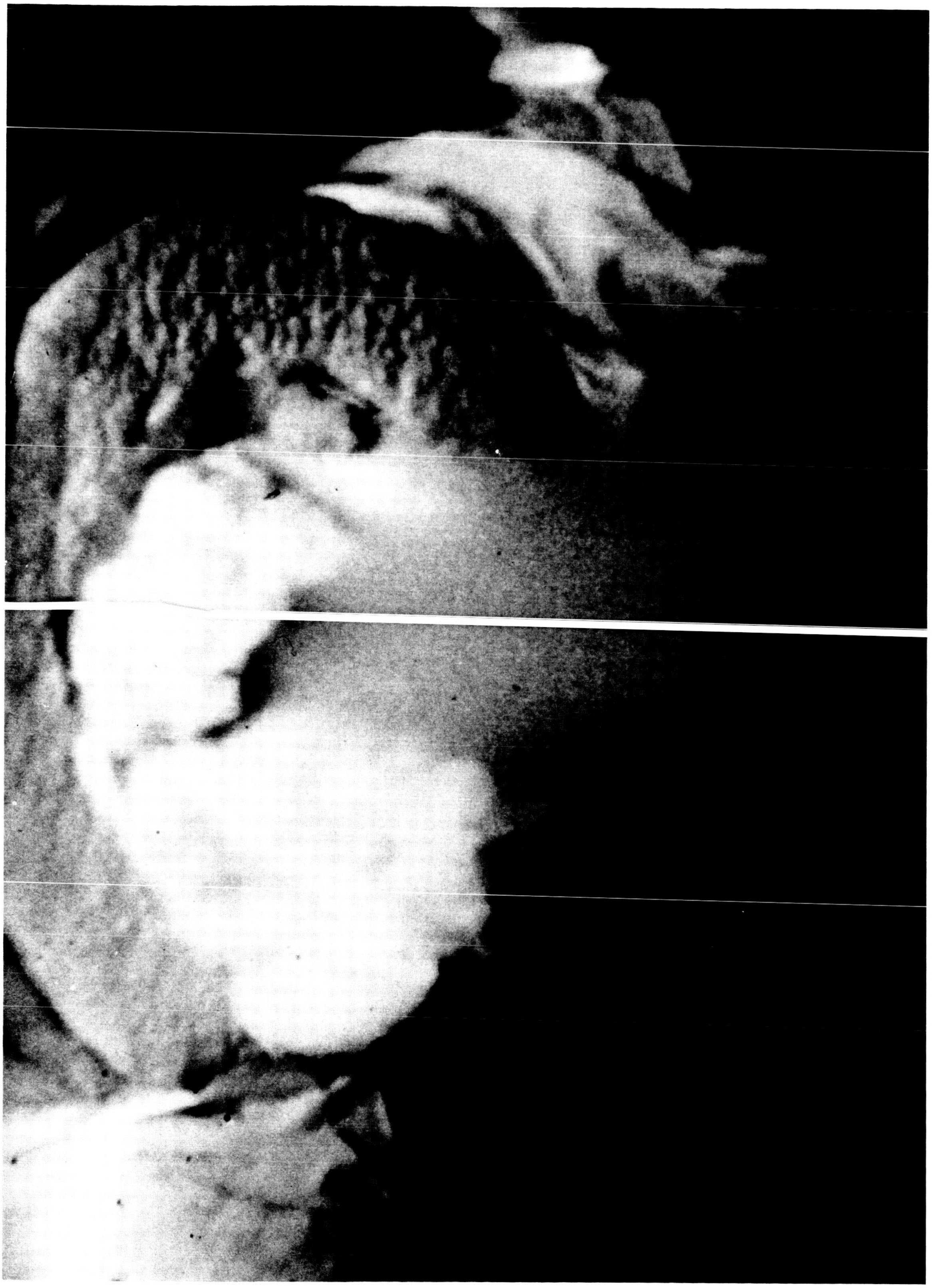

Figure III-1. Interstage Valve Vent Tube Showing 80% Blockage at a Fuel Pump Inlet Pressure of 15 psia   FE 52964F

DF 42301

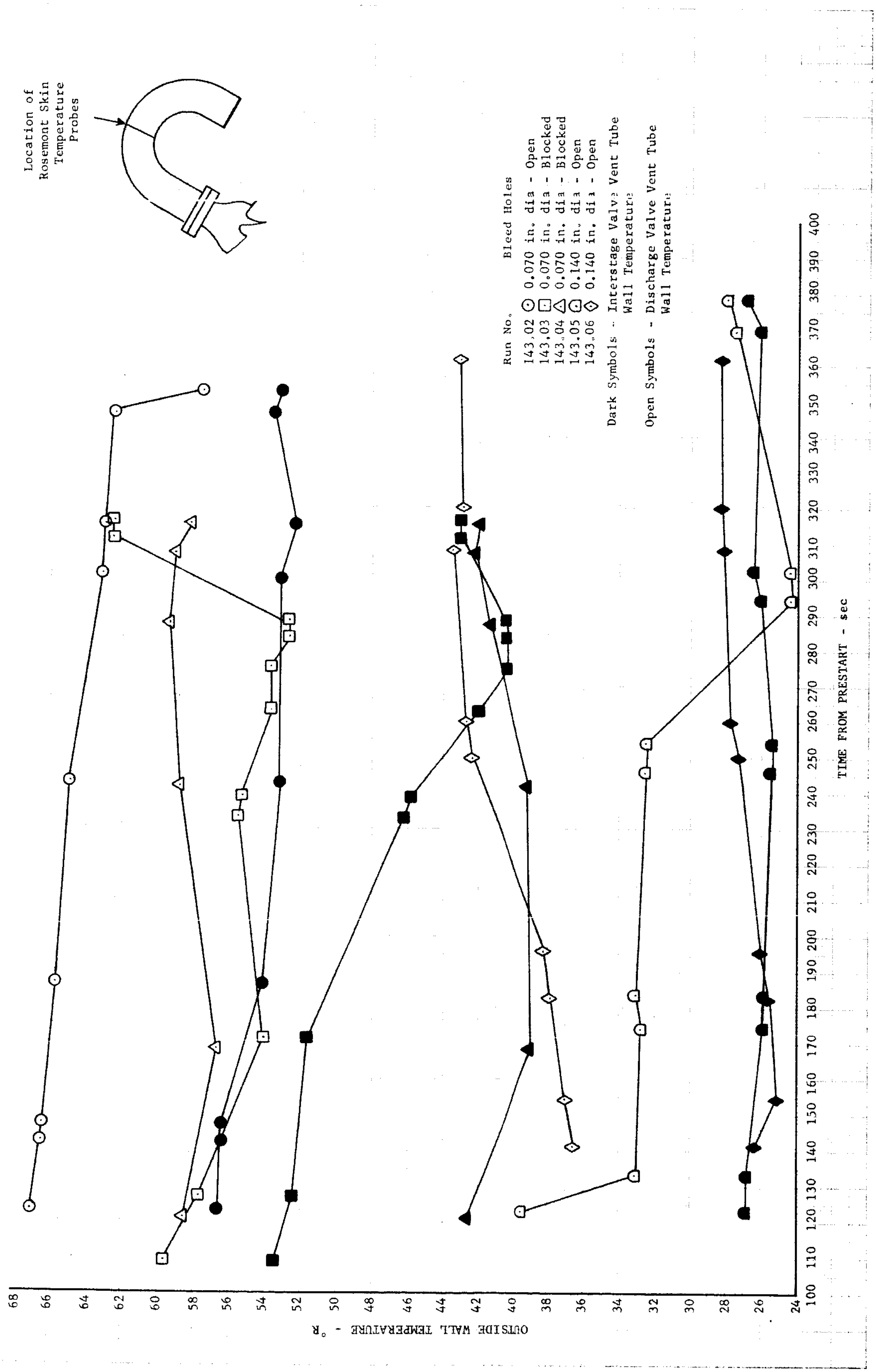

Figure III-2. Hydrogen Vent Tube Outside Wall Temperature

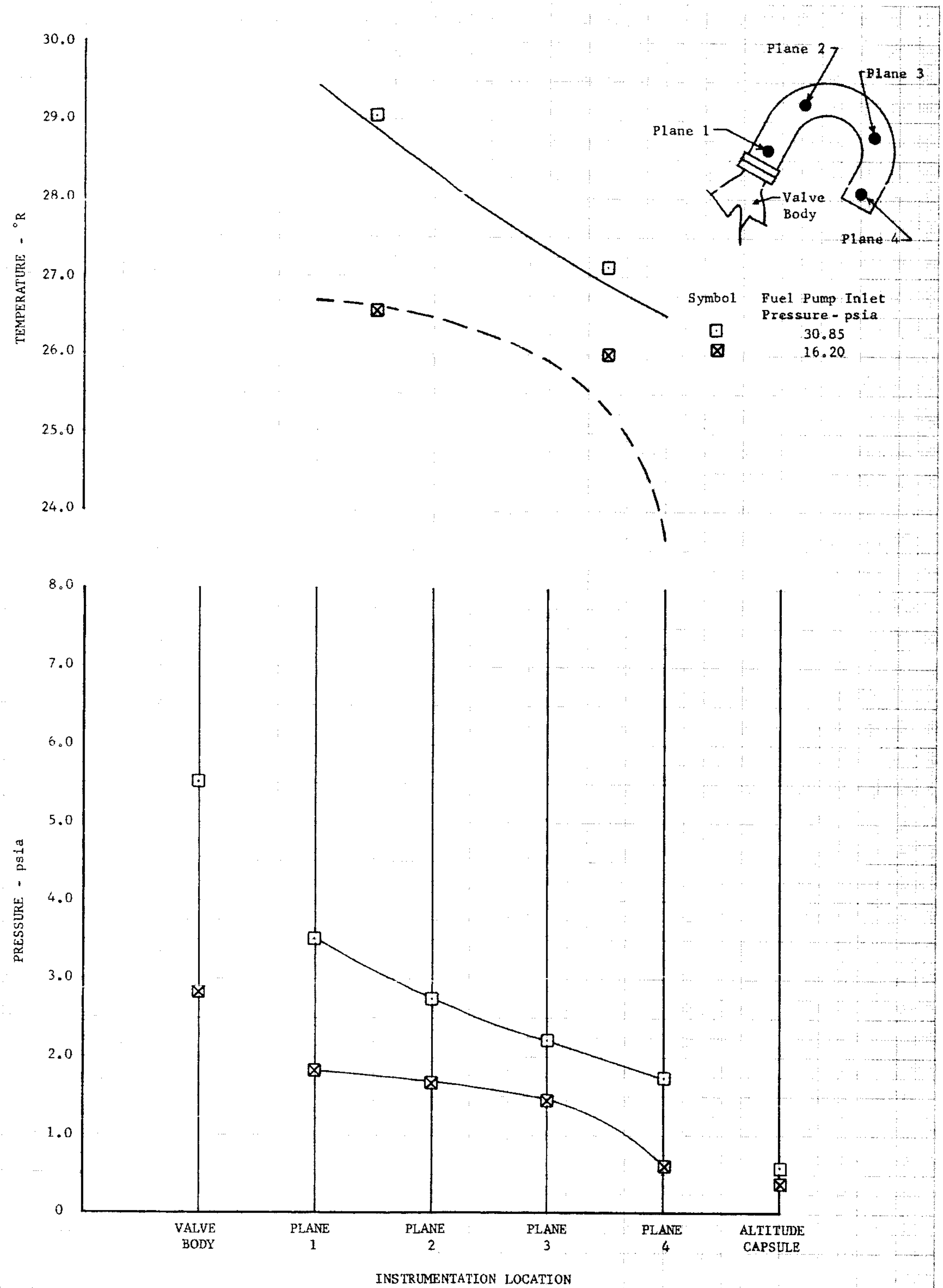

Figure III-3. Interstage Valve Vent Tube Pressure and Temperature vs Axial Length DF 42298

To reduce this heat input, some tests were conducted with film cooling on the outside of the tube by drilling small holes at the entrance to the tube. With four equally spaced 0.070-inch diameter holes, no change was noted in the heat input; however, when the holes in each tube were enlarged to 0.140-inch diameter the heat input dropped appreciably, as can be noted in table III-1. The photographs also showed that the 0.140-inch holes were open, since the flow could be seen discharging around the tube. However, the amount of solid hydrogen formed was not significantly different than on the runs without bleed flow.

The standard tube, with the foam insulation, was tested and although temperature data were not recorded, the large quantities of solid hydrogen formed at the vicinity of the triple point pressure indicated that the heat input must have been low.

It should be noted that up to run No. 143.03, the camera lights were on during the entire run at high intensity (approximately 600 watts). Since this was considered to be a possible contributor to the heat leak, all of the subsequent runs were made with the light intensity reduced and used only during the actual camera operation. From table III-1, it can be seen that the measured heat input was reduced to the interstage valve vent tube; however no change in the amount of solid hydrogen formed was noted.

The majority of all testing done was accomplished at environmental pressures of approximately 0.4 psia. The vent tubes were choked except when the environmental pressure was intentionally raised above 1.0 psia.

The amount of heat needed to prevent the solid hydrogen from forming on the tube walls is estimated to be above 1.0 Btu/sec, which is approximately the highest heat input at which solid was observed. The breakdown of the estimated available heat sources in space is presented in table III-2. It is obvious that there is not sufficient heat from radiation to prevent the solid from forming.

Table III-1. Heat Transfer Summary
Engine FX-145-14

Run[4]	Tube Heat Input, Btu/sec[1,2] Discharge Valve Vent Tube	Interstage Valve Vent Tube	Type of Insulation	Bleed Flow Configuration	Camera Lights
143.01	Instrumentation Problems		Radiation Shield	Open[5]	High intensity, entire run
143.02	0.941	0.857	Radiation Shield	Open[5]	High intensity, entire run
143.03	0.788	0.837	Radiation Shield	Blocked[5]	High intensity, entire run
143.04	0.793	0.473	Radiation Shield	Blocked[5]	Low intensity, short bursts
143.05	0.042[3]	0.013[3]	Radiation Shield	Open[6]	Low intensity, short bursts
143.06	0.221[7]	0[7]	Radiation Shield	Open[6]	Low intensity, short bursts
143.07	Skin Temperature Data NAV		Foam	None	Low intensity, short bursts
143.08	Skin Temperature Data NAV		Foam	None	Low intensity, short bursts
143.10	Skin Temperature Data NAV		Teflon	None	Low intensity, short bursts

[1]Values quoted are at a fuel pump inlet pressure of 20 psia and a capsule pressure of 0.4 psia, unless otherwise specified.

[2]Based on outer skin temperatures obtained with the Rosemont skin temperature probes.

[3]Values quoted at a fuel pump inlet pressure of 16 psia.

[4]Runs 143.09 and 143.12 were gas flow tests, run 143.11 was an oxidizer test, and are not presented.

[5]Four equally spaced 0.070-in. diameter holes.

[6]Three 0.140-in. diameter holes.

[7]Assumes bulk temperature of 27°R.

Table III-2. Estimated Possible Radiation Sources for One Tube

Source	Heat Input, Btu/sec
Sun	0.033
Thrust Chamber and Nozzle	1.28×10^{-6}
Oxidizer Tank	0.25×10^{-6}

The effect of surface smoothness on the ability of the solid hydrogen to adhere to the tube wall was also investigated. On run No. 143.10, the inside tube wall was coated with Teflon; the solid hydrogen still adhered to the tube wall.

Runs were made with fuel pump inlet pressures regulated between 30 and 5 psia. This resulted in inlet conditions varying from liquid to two-phase flow. The discharge valve and interstage valve vent tube exit pressures varied from 1.8 to 0.2 psia with varying inlet pressures as shown in figure III-4.

The tube pressure profile is altered below 20 psia, especially on the interstage valve tube. Visual observation of the motion picture showed that at a fuel pump inlet pressure of 30 psia there was no buildup of snow in the tubes, at 20 psia there was small intermittent snow buildup and breakoff at the discharge end of the vent tubes, and at inlet pressures below 10 psia the snow buildup appeared to be forming up inside the tube.

On all runs up to No. 143.06, there were differential pressures measured between the tube inlets and exit planes. From these data it was seen that as fuel pump inlet pressures dropped below 20 psia, the differential pressures indicated intermittent snow buildup and clearing of the tubes. On run No. 143.05 a buildup was noted when the fuel pump inlet pressure dropped to 15-16 psia. This effect is shown by the tube inlet and exit pressures and by the differential pressure data shown in figure III-5.

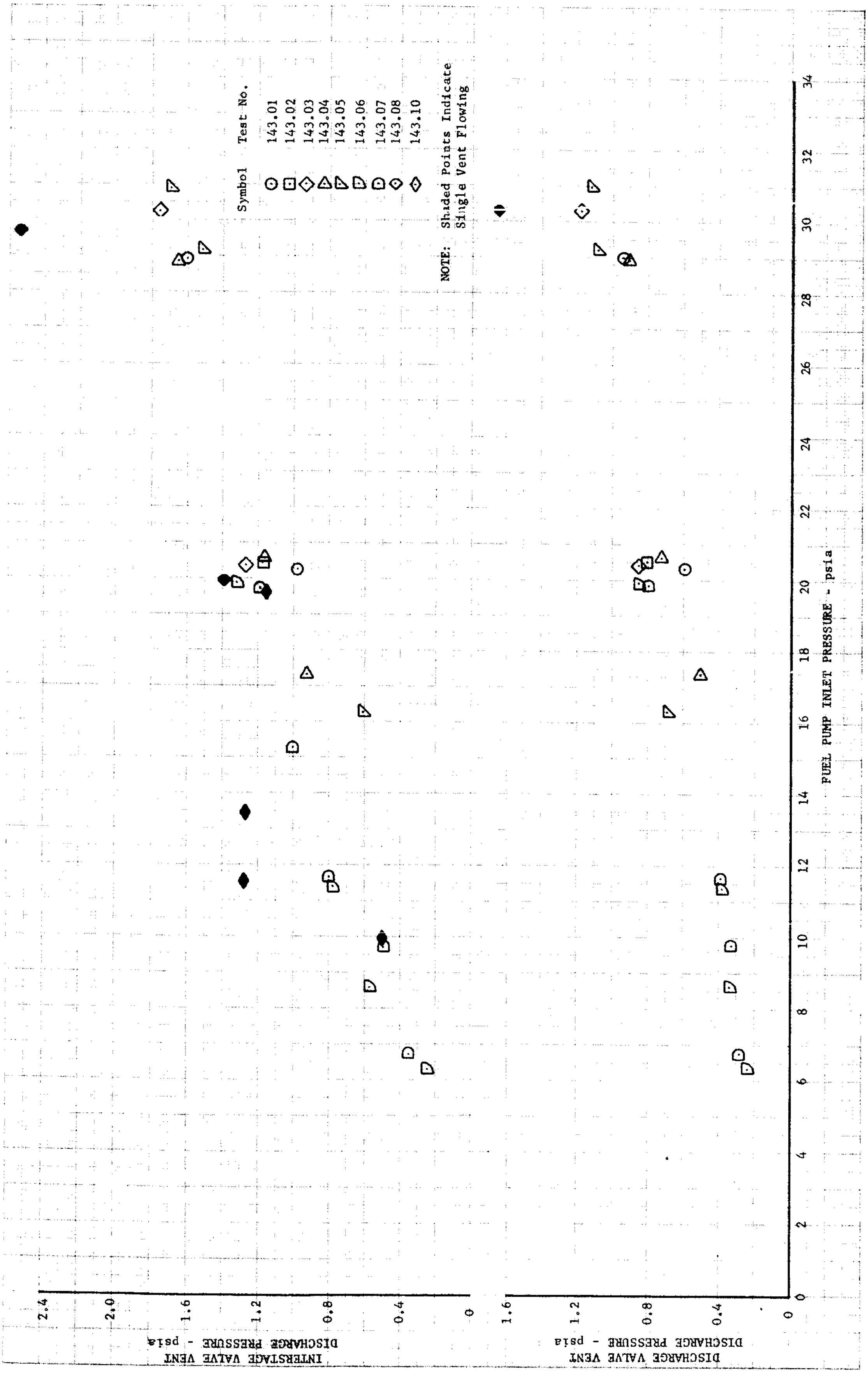

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Figure III-4. Variation of Discharge Pressure with Inlet Pressure

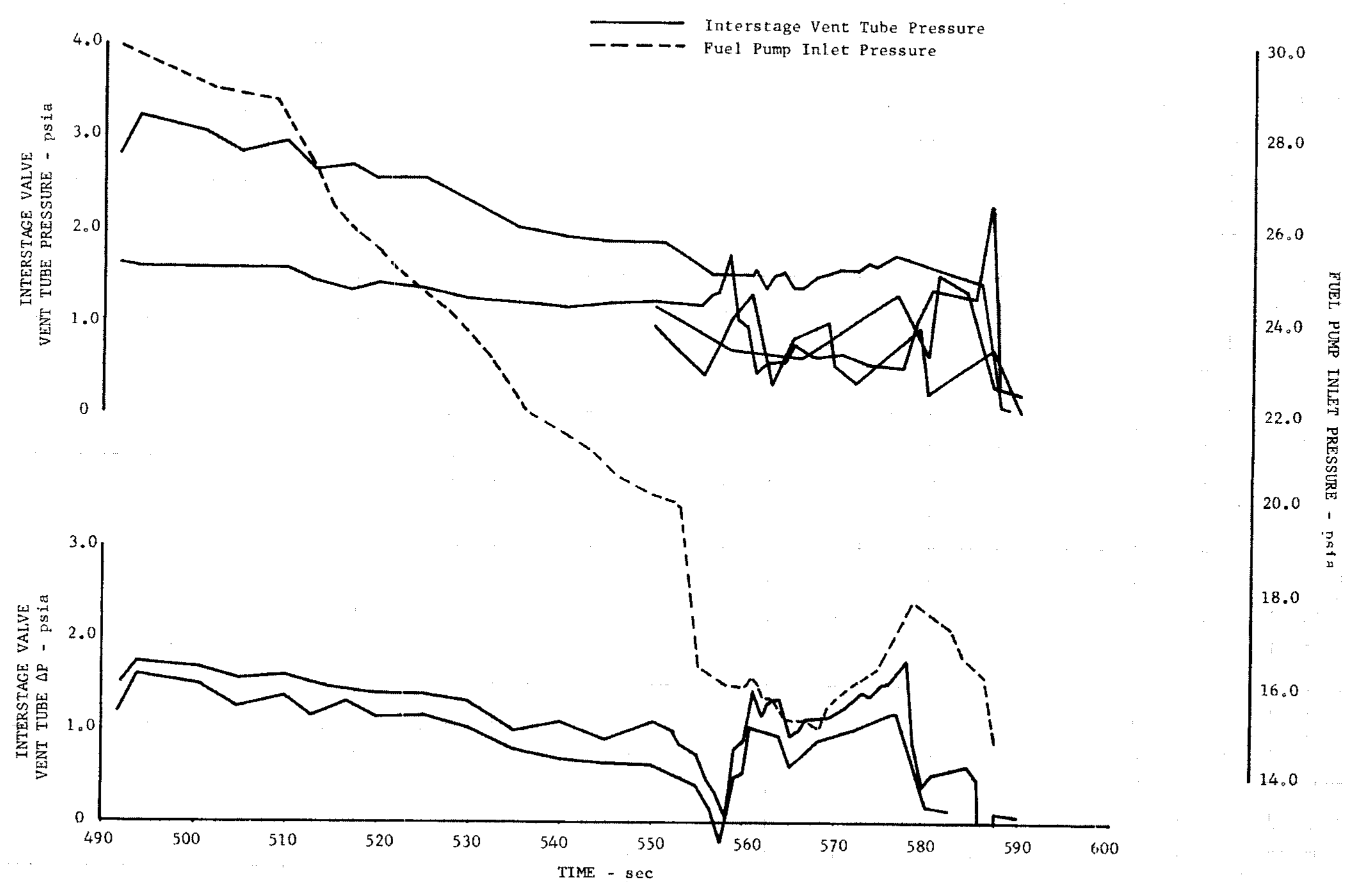

Figure III-5. Vent Tube Pressure Variation Due to Snow Formation

DF 42300

Visual observation of the motion pictures indicated that the interstage vent tube appeared to have a greater buildup of snow at the exit than the discharge valve vent tube. Because the discharge valve vent flow rate is lower than interstage valve vent flow rate, the tube wall temperatures could be higher; thus, reducing the tendency for the snow to attach to the tube walls. It is also possible that the snow may build up nearer the tube entrance and could not be seen in the motion pictures.

On run No. 143.03 and No. 143.04, the vent tube back pressure was raised by flowing ambient hydrogen gas into the can, to allow verification that the tube exits were choked. Analysis of all data where the back pressure was not raised indicated that the tubes were choked. These data indicate that the discharge valve vent unchoked at a back pressure of approximately 1.0 psia, and interstage valve vent tube did not unchoke.

Reducing the heat leak by exterior cooling flow caused more erratic changes in exit pressure, indicating more tendency for snow buildup. On run No. 143.07, with the standard insulated GD/C vent tubes, the snow buildup effect was significantly increased.

On run No. 143.06, the fuel pump inlet pressure was reduced to 10 psia, which resulted in several flow interruptions accompanied by a decrease of the inlet pressure to 5 psia. It is suspected that these interruptions were caused by gas bubbles formed upstream of the engine fuel pump inlet. In subsequent runs, a higher fuel pump inlet pressure was utilized, and the stand dump lines were opened to increase the flow rate in the lines.

Run No. 143.10 was conducted with the interstage vent tube internally coated with Teflon-filled Kel-F. No significant reduction in snow buildup was observed due to the smooth interior surface or any insulating values of the Teflon.

Temperature differentials between the immersion (bulk) probes and the skin probes indicated a significant heat leak into the tubes. Several changes were made to verify this heat leak. A temperature probe was placed between the wrapped insulation and the tube. This probe read overscale, except when flow was passed between the insulation and the tube. Thermocouples near the tube exits indicated 80 to 100°R, even when the tube external flow showed snow formation. The initial thermocouple installation was made by mounting the wires on a piece of shim stock and gluing this to the tube with epoxy glue. On latter runs, holes were drilled in the tube and the thermocouple wires imbedded in the holes and then glued down with aluminum powder impregnated epoxy. No significant change in temperature readout was obtained by this modification.

During the 1st through the 3rd runs, high intensity camera lights were utilized throughout the runs. These lights were causing an unnecessary heat load on the tubes. From the 4th run to the end of the program, the camera light intensity was reduced by 50%; the lights were only turned on when the motion pictures were being taken. This resulted in a reduced heat leak.

It was noted that the bulk temperatures varied as the pressure level was decreased. The measured temperature near the tube exit read an increasing differential above the saturation temperature. A calculation of the Mach number, assuming gaseous flow and Mach 1.0 at the tube exit and using both the Fanno and Raleigh relationship, indicates velocities above Mach 0.9. The total temperature was then calculated assuming the static temperature to be the saturation temperature. When the measured temperature was compared to the calculated total temperature, it was found that the two temperatures approached as the pressure decreased, but never agreed. The following theory tends to explain this characteristic. The flow is two-phase and some of the liquid or solids will probably collect on the downstream side of the probe, which results in a gas stagnation temperature on the front of the temperature element. A liquid saturation temperature quality increase allows less liquids or solids to collect on the probe, thus permitting the probe readout to approach the gaseous total temperature.

The effective areas for lox bleeddown flows was determined by a lox flow test during run No. 143.11. An orifice near the lox pump inlet was used to keep the meter flow liquid when the inlet was two-phase and a measured flow was passed out the stand dump line to keep a high meter flow rate.

It is possible that solid hydrogen impingement may cause damage to the Surveyor spacecraft. From the photographic data the size and velocity of a representative fragment of solid hydrogen was determined thus allowing the momentum to be calculated. To define a limit, the momentum was also calculated for a hypothetical case when the solid hydrogen completely blocks the tube exit to a depth of 0.5 inch and is then ejected in one piece. The volume of the fragment was determined to be 0.095 $in.^3$ and the velocity was 146.7 ft/sec, producing a momentum of 0.039 lb_m-ft/sec.

SECTION IV
CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The solid hydrogen adheres to the vent tube walls and could possibly block the tubes completely unless the process is self-compensating; i.e., either by limiting the solid formation or by forcing the solid hydrogen from the tube by the resultant pressure drop. However, even partial blockage will affect the flow and thrust characteristics. The maximum observed blockage was approximately 80% with the foam insulated vent tube. It should also be noted that the discharge valve vent tube had consistently less solid formation, even though lower pressures exist in this tube.

The tests reproduced space conditions except for the indicated high heat input of approximately 0.8 Btu/sec during some of the earlier runs.

With the present mission and configuration in space, there is not sufficient heat input to the tubes from radiation to prevent the solidification of the hydrogen on the tube walls. There is approximately 0.03 Btu/sec available to the tube, while the estimated required amount is above 1.0 Btu/sec, which is approximately the highest heat input at which the solid was still observed. A more complete summary of the available heat sources is given in table III-2. Teflon coating the inside of the discharge valve vent tube had no noticeable effect on the ability of the solid hydrogen to adhere to the tube walls.

B. RECOMMENDATIONS

Modifications to either the vehicle or engine should be designed and tested that will prevent the formation of solid hydrogen or cause the formation to have a negligible affect on the Centaur Retromaneuver. These modifications should include the following items.

1. Orifice at Exit of Vent Tube

An orifice could be incorporated at the exit plane of each vent tube that would raise the pressure throughout the vent tube above the triple line pressure of 1.0 psia. Figures IV-1 and IV-2 present the estimated effect on vent tube pressure of the orifice size and the pump inlet pressure. Although it appears that these curves do not agree with the observed solid buildup, it should be noted that the solid formations observed in the photographic data occurred at the tube exit plane and not at the upstream plane where the last pressure taps were located. Also, the curves represent a steady-state condition, whereas the photographs showed the solid hydrogen continually building up and breaking away; thus making it difficult to relate to the recorded pressure data. Important to the assumption that the solid hydrogen will act as an orifice is the knowledge of how the solid hydrogen forms, and then its subsequent behavior after the pressure has increased above the triple line pressure. For example, if the two-phase flow expands past the solid hydrogen orifice and solidifies much more rapidly than the melting of the solid hydrogen due to the increased pressure, it might precipitate an adverse blocking condition.

2. Helium Purge

Residual helium on board the vehicle could be used to purge both vent tubes during the retromaneuver. This would provide both a heat source and a boundary layer on the interior surface of the tube that would prevent the solid hydrogen from adhering to the wall, and would also provide a scrubbing action to break off formations.

3. Increased Tube Wall Temperature

Heat could be added to the tube wall through use of heater strips or a heater blanket that would increase the wall temperature high enough to preclude the possibility of solid hydrogen formation. It is estimated that this would require a minimum power of 1 kw for each engine.

4. Increased Diameter Vent Tube

The diameter of the vent tube could be increased so that the solid hydrogen would not be able to withstand the bending stresses caused by hydrogen stream velocity as it accumulated on the tube wall. However, the exact geometry of the solid buildup and the strength data of solid hydrogen are not known.

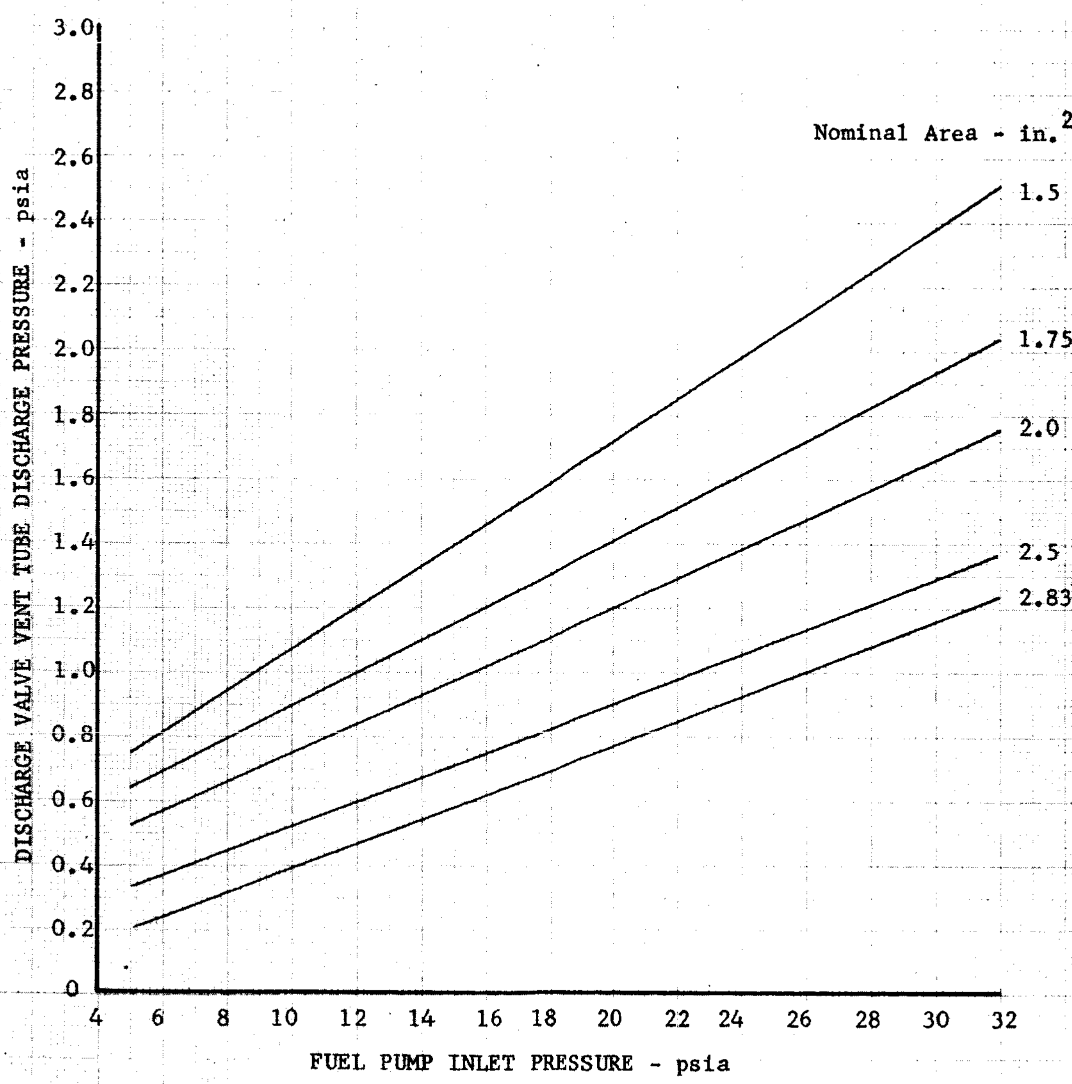

Figure IV-1. Estimated Vent Tube Pressure as a Function of Fuel Pump Inlet Pressure and Discharge Valve Vent Area DF 42303

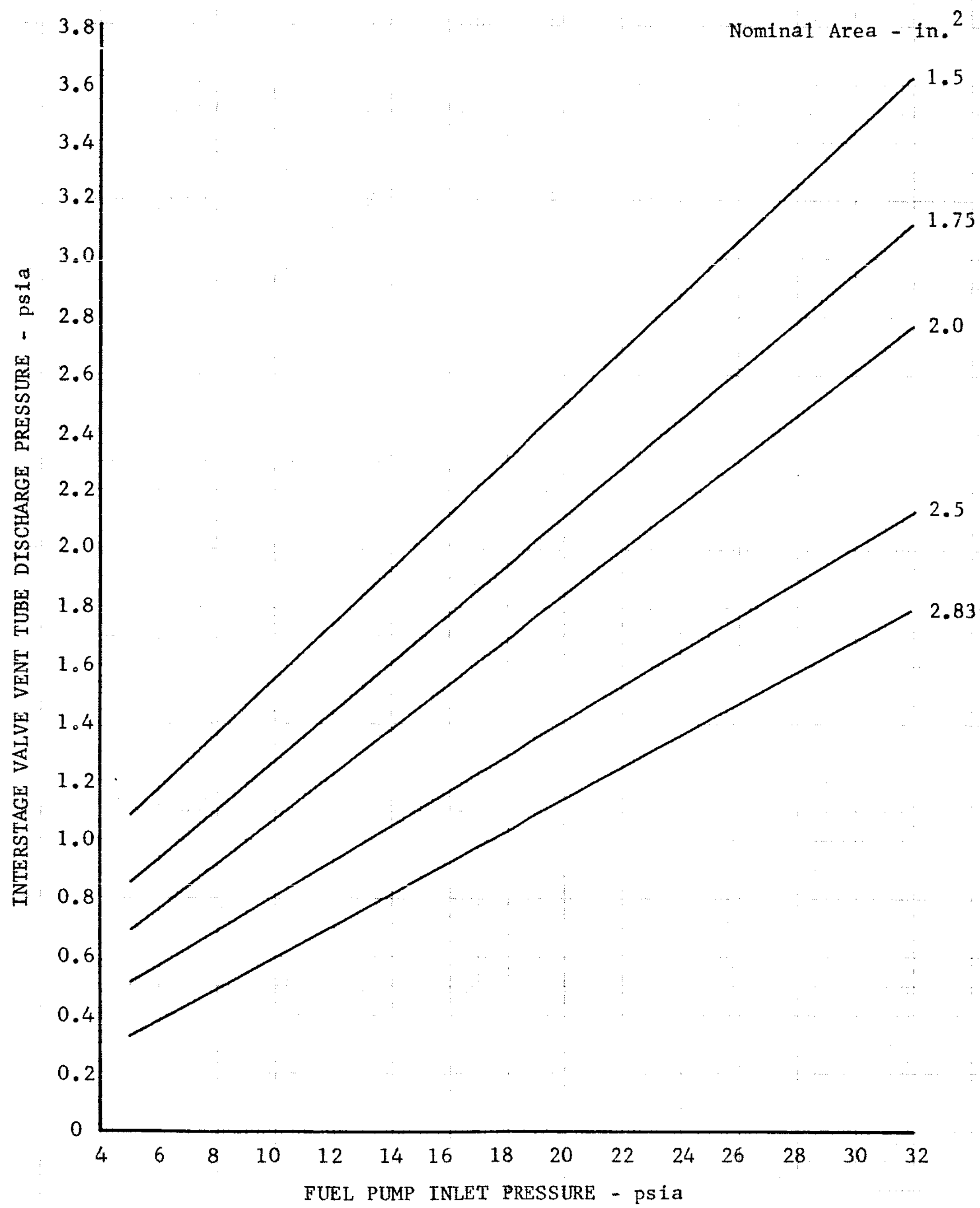

Figure IV-2. Estimated Vent Tube Pressure as a Function of Fuel Pump Inlet Pressure and Interstage Valve Vent Area

DF 42302